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Phase coherent electron transport in open quantum dots and quantum dot arrays

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Abstract. Recent studies of coherent electron transport in open quantum dots and quantum dot arrays are reviewed. Our interest focuses on the connection between the quantum and semi-classical descriptions of transport in these structures, which provide ideal systems for the experimental study of quantum chaos.

1. Introduction

An important issue in the study of quantum chaos concerns the connection between the discrete level spectrum of a strongly confined quantum system and the periodic-orbit structure of its corresponding classical counterpart. Semiconductor quantum dots [1, 2], consisting of a sub-micron-sized cavity coupled to quantum point contact leads, are ideally suited for the study of this problem. The discrete density of states in these dots remains well resolved in experiment, even with the point contacts configured to support a number of propagating modes [3]. At temperatures well below a degree Kelvin, the magneto-resistance of these devices exhibits highly regular and reproducible fluctuations, which may be interpreted as arising from a spectroscopy of the discrete density of states of the dot [3–5]. Equivalently, the oscillations may be associated with the interference of a small number of semi-classical orbits within the dot. These transport features therefore provide a connection between the density of states of the dot and its periodic orbits. In this invited contribution, we review our recent studies of coherent electron transport in open quantum dots. We discuss how, by modifying the details of the coupling between the dot and its quantum mechanical leads, it is possible to select different wavefunction states, giving rise to directly measurable transport results. We also briefly discuss our more recent studies of open dot arrays [6], which reveal evidence for *collective* transport signatures when the coupling between the dots is sufficiently strong.

2. Experimental details

Both the fabrication and basic characterization of the devices we study are described in detail elsewhere [5]. Split-gate quantum dots and quantum dot arrays were formed on the surface of GaAs/AlGaAs heterojunction wafers using electron-beam lithography and metal-deposition techniques. At 4.2 K, the carrier density of the samples was found to vary from $3.8-5.5 \times 10^{11}$ cm^{-2}, while the electron mobility was as high as 1,000,000 cm^2/Vs.

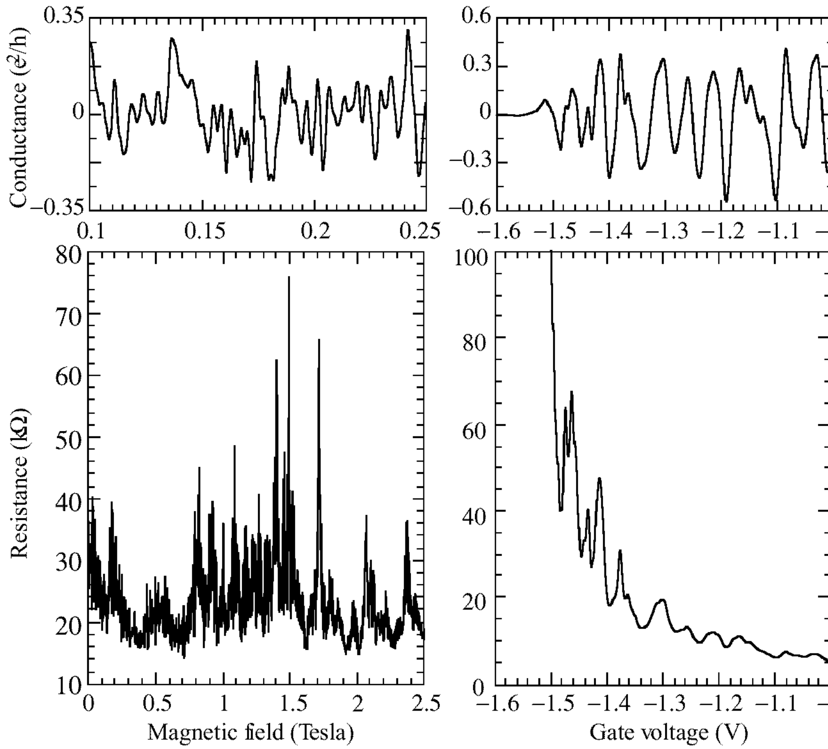

Fig. 1. Conductance fluctuations in single quantum dots. Shown left is the result of a magneto-resistance measurement performed on a 1-μm square (lithographic size) dot. The upper panel shows the conductance fluctuations measured at weak fields (a smooth background has been extracted from this data). Shown right is the gate voltage characteristic of a 0.4-μm dot whose conductance fluctuations are plotted in the upper panel (again after subtraction of a monotonic background).

Unless stated otherwise, resistance measurements of the devices were made at the base temperature of a dilution refrigerator (0.01 K), using lockin detection and small constant currents ($\leq$1 nA).

3. Transport studies of single dots

In Figure 1, we show typical results of measurements of the conductance of single dots as a function of magnetic field and gate voltage. At the low temperatures considered here, electron phase coherence is maintained over long distances [7, 8] and the discrete level spectrum of the dot remains well resolved, in spite of the coupling that exists between the dot and the quantum point contact leads [3]. The conductance fluctuations observed in Fig. 1 then result as the magnetic field or the gate voltage is used to sweep the discrete states of this spectrum past the Fermi level [3–5].

An important feature of the conductance fluctuations shown in Fig. 1 is their highly regular nature. This property is confirmed by a Fourier analysis of the fluctuations, which reveals the presence of a small number of dominant frequencies at discretely separated values [3, 5]. This characteristic suggests that transport through these dots is dominated by a small number of orbits. Furthermore, the experimental finding that the frequency

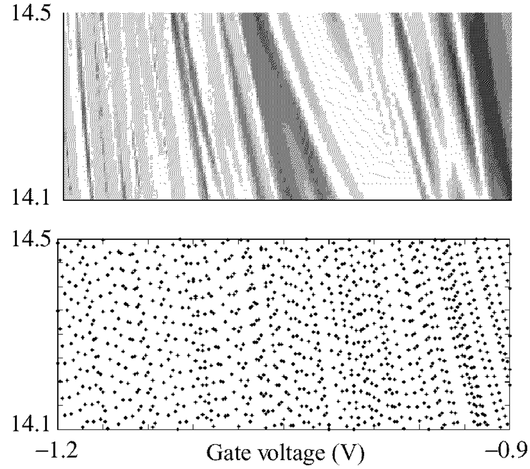

Fig. 2. Lower panel: evolution of the closed dot eigenstates with gate voltage. The lithographic size of the dot is 0.4 μm but the dot profile employed in the Schrödinger equation is computed self-consistently. Upper panel: the conductance contour plot obtained for the corresponding open dot. Darker regions correspond to higher conductance and the grayscale plot varies from $0-2e^2/h$. In both of these figures, the vertical scale corresponds to energy in meV.

content of the fluctuations does not depend sensitively on gate voltage points to the highly *stable* nature of these orbits [5]. Temperature dependent studies show that the fluctuations disappear on warming to above a degree Kelvin, indicating they are built up in a highly recursive process in which electrons undergo multiple traversals of the same basic orbits while maintaining their phase coherence [5]. In support of this notion, it has been found possible to reproduce the dominant experimental frequencies in numerical simulations of *classical* cavities in which electrons are assumed to be injected into the dot in a highly-directed, or *collimated*, beam [9]. The collimation is generated by the quantum point contact leads, which are configured to support only a small number of one-dimensional modes. Electrons entering these leads from the external reservoirs may therefore only do so by matching their transverse momentum component to one of the discretely quantized values within the contact itself.

While the discussion above attributes the conductance fluctuations to an interference effect involving a small-number of semi-classical orbits, they may also be understood to arise from quantum-mechanical mode-matching considerations between the central dot and the one-dimensional leads [3, 4]. According to this interpretation, the fluctuations provide a "spectroscopy" of the discrete level spectrum of the open dot. The crucial point here is that the use of quantum point contacts to couple the dot to the external reservoirs does not obscure its discrete energy spectrum. Rather, it results in a small set of dot states being preferentially excited in transport. The connection between the eigenstates of a closed dot and the conductance of its open counterpart can be seen in Fig. 2 (for further details on the numerical simulations we refer the interested reader to [5, 9]). Note how the energy levels of the isolated dot shift almost linearly over the entire range of gate voltage shown. A similar variation is also apparent in the conductance contour of the open dot; the linear striations that run through this grayscale plot clearly follow the motion of certain closed-dot states, indicating that these states play a strong role in mediating transport through the open dot. Crucially, however, *we note that not all states of the isolated dot give rise to a*

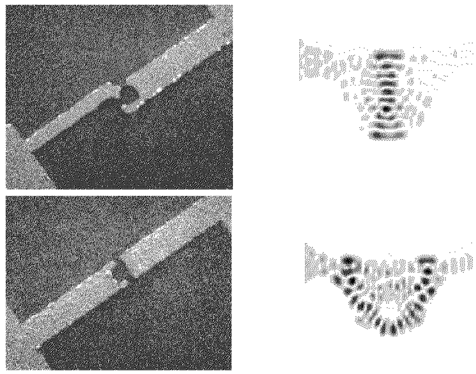

Fig. 3. Split-gate quantum dots used to investigate the influence of lead orientation on quantum dot transport. The lithographic size of both dots is 0.4 μm. Shown right are examples of scars that occur in the dot geometry with oppositely aligned quantum point contact leads. Darker regions correspond to enhanced probability density.

marked modulation of the conductance of its open counterpart. Instead, the conductance provides a *filtered* probe of the density of states of the closed dot. As we discuss in greater detail in [4], similar considerations have also been found to apply to the results of magneto-conductance measurements. In these, the magnetic field sweeps the density of states of the open dot past the Fermi level and the resulting oscillations in the conductance also provide a spectroscopic probe of the open dot [4].

An important conclusion of these studies is that the transport properties of open dots are critically influenced by the details of their *coupling* to the external environment. (This conclusion is further suggested by studies of the phase-breaking time in these structures [8].) An interesting possibility is that it should therefore be possible to *modify* electron transport in the dots, simply by changing the *orientation* of their point contact leads. In order to investigate this possibility, we have fabricated dots whose leads are positioned at different points on their perimeter (Fig. 3) [3]. The conductance fluctuations in these dots show different frequency content, which we attribute to the role of the leads in coupling to different dot states [3]. Numerical studies show that the wavefunction in the dots is strongly *scarred* by the remnants of a small number of semi-classical orbits. Consistent with the discussion above, the scarring is thought to result from the interference of orbits that are preferentially excited through their coupling to the leads. As the gate voltage is varied, the scars are found to *recur* periodically with frequencies that correspond very closely to the dominant components of the conductance fluctuations in experiment. The simulations also show that the different fluctuation frequencies measured in the different dots is correlated to the recurrence of different kinds of scars in these geometries [3]. That is, it would appear that, simply by changing the nature of the coupling between the dot and its external environment, it is possible to excite different wavefunction states, giving rise to directly measurable transport results.

4. Transport studies of quantum dot arrays

In coherently-coupled arrays of dots, the transport behavior should be somewhat more complicated than that discussed above, since the details of electron interference in any one dot will now be determined by the nature of the *collective* coupling that exists to the other dots in the array. Motivated by this consideration, we have studied the nature

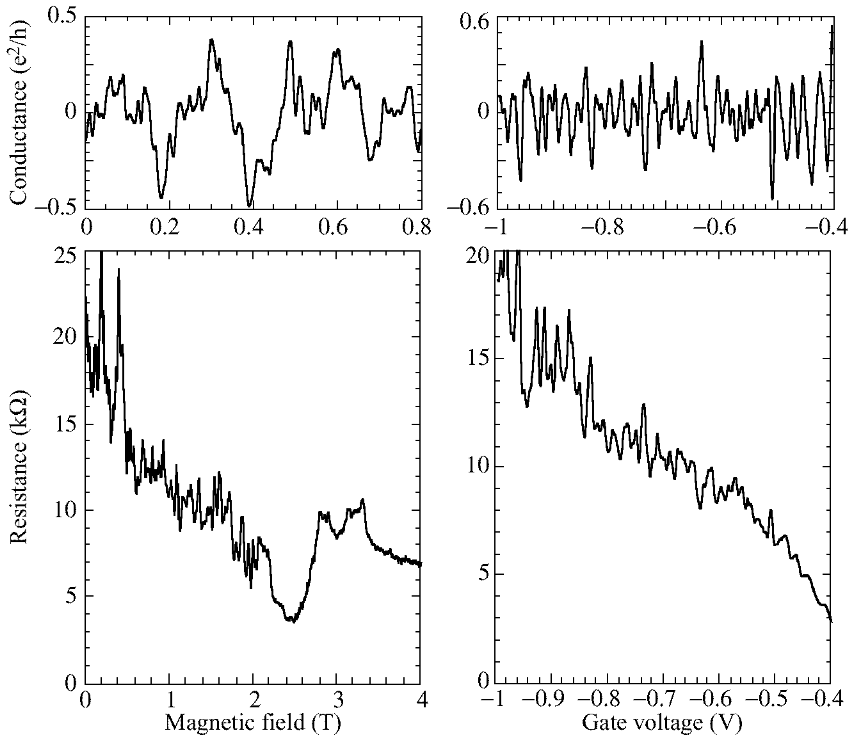

Fig. 4. Conductance fluctuations in a quantum dot array, consisting of three identical dots of lithographic size $1.0\,\mu\text{m} \times 0.6\,\mu\text{m}$. In order to obtain the conductance fluctuations shown in the upper panels a monotonic background has been subtracted from the raw data.

of coherent electron transport in linear quantum-dot arrays and in Fig. 4 we show the results of measurements of one such array. While in many regards the behavior shown here appears reminiscent of that found in studies of single dots, a Fourier analysis of the magneto-conductance fluctuations shown here reveals that, as the coupling between the dots is increased by opening the quantum point contact leads, a marked increase in the *high-frequency* content of the fluctuations occurs. We believe that this increase may signal an evolution from single-dot, atomic like, transport to *molecular-like* behavior in the arrays. Further studies are currently underway to investigate this possibility, however.

5. Conclusions

Our recent studies of coherent electron transport in open quantum dots and quantum dot arrays have been briefly reviewed. These devices are particularly suited to experimental studies of quantum chaos, since they reveal a picture in which electron transport is dominated by the excitation of a small number of stable orbits. These orbits are selected by means of coupling conditions between the dot and its quantum mechanical leads. At low temperatures, where phase coherence is maintained over long distances, electrons that undergo multiple traversals of these orbits give rise to strong wavefunction scarring and associated transport results.

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